Oil spill trajectory on the northern British Columbia coast: results from a series of numerical simulations

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Table of Contents

List of Figures iv
List of Tables v
Abstract vi
Résumé vii
1. Introduction 1
2. BC Coast ROMS and LTRANS software 1
3. Regional winds and ocean currents 2
4. Setup of the oil spill source location 3
5. Results 4
    5.1 An example of the particle movement 4
    5.2 Temporal and spatial variability of the oil distribution 5
    5.3 Probability of impact of oil spill on remote coastal areas 6
6. Discussion and conclusion 6

References 7

List of Figures

Figure 1. Enbridge proposed tanker routes, and source area of simulated oil spills (purple area).

Figure 2. Seasonal wind roses computed from the 10 year integration period, at 130°W, 52°45'N. The size of the pink triangles indicates the frequency by wind direction (coming from). The blue line indicates the mean amplitude of the wind in each direction.

Figure 3. Mean seasonal surface currents over the 10 year simulation (a: winter, b: spring, c: fall, d: summer). The contours indicate the mean sea level (m).

Figure 4. Distribution of oil droplets, 15 days after their release from one single point source (indicated by the star), during the fall season. In blue are the daily covariance ellipses (see main text for details).

Figure 5. As in Figure 4, but for winter.

Figure 6. As in Figure 4, but for spring.

Figure 7. As in Figure 4, but for summer.

Figure 8. Seasonal vertical distribution of the oil droplets released from the test location (star on Figure 1).

Figure 9. Probability (%) for a droplet to be found within the source area, during the 15 day period following its release.

Figure 10. 10-year average horizontal particle distribution (%), over the 15 day integration period.

Figure 11. As in Figure 10, but for each season.

Figure 12. Source area (pink), as well as 5 remote coastal areas (orange: Central BC, blue: northern BC, olive: Alaska, violet: Graham Island, Green: Moresby Island).

Figure 13. Occurrence (%) of the droplets in the coastal zones identified in Figure 12.

Figure 14. Seasonal relative occurrence (%) of the droplets within the North Shore Region.

Figure 15. As in Figure 14, for the Central Shore area.

Figure 16. As in Figure 14, for the Southern Alaska area.

Figure 17. As in Figure 14, for the Moresby Island area.

Figure 18. As in Figure 14, for the Graham Island area.

List of Tables

Table 1. The fraction (%) of oil droplets found within the source area, in the 15 day integration period.

Table 2. The fraction (%) of oil droplets found within each of the remote coastal areas.

Abstract

In this study, the movement of oil spilled on the east shores of Hecate Strait, British Columbia, is simulated using a local implementation of the Regional Ocean Modeling System (ROMS) and the Larval TRANSport Lagrangian model (LTRANS). The oil droplets are represented as neutral buoyancy particles and their movement is forced by the ocean currents and diffusion by ocean turbulence. Statistical properties of the mean distribution of the particles are presented, as well as their seasonal variability. The resulting simulated distribution is found to vary significantly with seasons, with a wider distribution in summer when the wind direction is more variable. In fall and winter, when northward wind prevails, the majority of the particles drift northward along the coast of BC and Southern Alaska.

Résumé

Dans cette étude, le mouvement du pétrole déversé sur la côte est du détroit d'Hécate, en Colombie-Britannique, est simulé en utilisant le Regional Ocean Modeling System (ROMS) et le modèle Lagrangien Larval TRANSport (LTRANS). Les gouttes de pétrole sont représentées comme des particules de densité neutre et pour lesquelles le déplacement est forcé par les courants et la turbulence océaniques. Les propriétés statistiques de la distribution moyenne des particules sont présentées, ainsi que les changements associés aux saisons. Les résultats de la simulation numérique indiquent que la distribution des particules varie avec les saisons d'une manière importante. En été, quand la direction du vent est relativement variable, les particules couvrent une région plus grande. Par contre, à l'automne et en hiver, la majorité des particules se propage le long de la côte en direction nord, sous l'effet du vent du sud-est.

1. Introduction

Oil spill impacts on the marine environment depend on the physical properties of the oil, where it is spilled, where it goes, and what animals and plants, or people, are affected. Oil slicks can affect the ecosystem through smothering, where oil coats plants and animals, and by the less obvious toxic response to the oil. These impacts are most devastating when the oil affects environmentally sensitive coastal areas. Many sections of the northern BC coast, such as Moresby National Park and Naikoon Provincial Park, have been identified as ecologically and biologically significant (e.g. Gunton and Broadbent, 2012), and their integrity would be potentially threatened by proposed projects involving transportation of oil coastal BC waters.

The movement of an oil slick in the marine environment can be forecasted using high-resolution ocean modeling systems forced by high-quality, high-resolution forecasting weather models, together with real-time data acquisition. Such a modeling scheme constitutes an essential element in planning and preparing effective response strategies to combat hazardous oil spills at sea. Another way in which ocean models can be used to improve local oil spill preparedness is to estimate the statistical distribution of potential oil spill, using an ocean circulation hindcast model.

The present document describes estimates of the statistical distribution of oil spilled in the coastal waters adjacent to the entrance to Douglas Channel, on the northern British Columbia coast (Figure 1). This work is part of the Government of Canada World Class Tanker Safety System initiated in response to the Northern Gateway project proposal. In these numerical simulations, it is assumed that oil slick dispersal is due to advection by mean ocean currents and to diffusion by ocean turbulence. We also assume that oil droplets have neutral buoyancy such that they do not sink or rise in the water column due to gravity. In other words, their vertical movement can be modeled as passive neutral floats. These assumptions are obviously not fully realistic: the behaviour of real oil droplets is more complex, in particular in the case of diluted bitumen products (e.g. Environment Canada, 2013). However, this simplified approach allows one to estimate the part of oil movement directly forced by the ocean circulation, i.e. due to the wind, tides and density-induced ocean currents.

2. BC Coast ROMS model and LTRANS software

To estimate the pathway of oil droplet movement, an implementation of the Regional Ocean Model System (ROMS) for the BC coastal ocean (Masson and Fine, 2012) is used. The model domain extends from the Columbia River to the Alaska Panhandle and is applied to hindcast the 10 year period 1998–2007. The horizontal resolution is 3 km, with 31 levels in the vertical.

ROMS is a terrain following, primitive equation model which has been used extensively to model various regions of the world's oceans. It is forced by NARR (North American Regional Reanalysis, 2004) atmospheric data, and lateral boundary conditions are extracted from the Simple Ocean Data Assimilation project, or SODA (Carton and Giesse, 2008). Tidal forcing is applied at the open boundaries using the output from a North-East Pacific tidal model (Foreman et al, 2000). In addition, the ocean model is forced by fresh water monthly discharge from BC major rivers, derived as in Morrison et al, 2012. Details of the model setup as well as an extensive model validation can be found in Masson and Fine, 2012.

The movement of the oil droplets is simulated in off-line mode, using modified LTRANS software (North et al, 2011), forced by the ROMS model output. LTRANS follows the path of particles in three dimensions using advection, mixing, and particle behavior. A 4th order Runge–Kutta scheme is used for particle advection. Particle motion due to sub-grid turbulence is replicated by a random displacement model component. Using such an off-line approach allows the computing extensive ocean circulation model and the oil spill drift simulation to be run independently, allowing multiple oil drift simulations to be easily done.

3. Regional wind and ocean currents

The local ocean currents will vary under the influence of tides, freshwater discharge, and winds. In particular, the seasonality in local wind forcing has a determinant role in establishing the seasonal features of the regional ocean circulation. Figure 2 gives the seasonal characteristics of the local wind, as a 10 year average of the wind vectors at a point central to the area of interest (130°W, 52°45'N). Regional coastal winds typically blow parallel to the coast, and are generally stronger during the storm seasons of fall and winter. The dominant wind direction is from the southeast (downwelling), particularly in the winter months when the Aleutian low has a strong impact on the local weather. In summer, conditions are less severe, with fewer storms and winds coming from both the southeast and northwest.

The surface ocean currents along the coast of northern BC are presented in Figure 3, for each season. Along the coast, under the influence of the dominating southeast winds and abundant freshwater coastal input, the coastal current flows to the northwest for most of the year. The exception is the summer months, when reduced freshwater flow and more variability in the wind direction result in a weaker, less unidirectional coastal flow (Fig. 3d). Another seasonal feature in the surface current is the presence of a well-defined anticyclonic circulation pattern present, in spring and summer, over Goose Island Bank (lower left corner, Fig 3b and 3c).

4. Setup of the oil spill source location.

According to a recent Northern Gateway Project Plan (e.g. Northern Gateway Pipelines Inc, 2010), there are 2 main options for the tanker route (Figure 1): the northern approach through Dixon Entrance (route 3), and the southern direct approach through Queen Charlotte Sound (route 1). In addition, a third route (route 2) is considered from the south, via Principe Channel, in case of severe weather conditions.

It is reasonable to assume that, along the proposed tanker routes, the risk of oil spill will be higher in the vicinity of the shoreline (e.g., Gunton and Broadbent, 2012). Accordingly, we have defined the modeled oil spill source area as the coastal ocean near the coast, along the proposed routes (see Figure 1). In this study, the narrow coastal passages, such as the upper Douglas Channel, are not included in the modeled source area because 1) the BC Coast ROMS does not resolve these passages well with its 3 km resolution, and 2) the oil from a spill within the interior passages will transit through the chosen source area on its offshore drift.

In order to simulate the oil spill drift patterns, a series of assumptions are made:

1) The oil droplets have neutral buoyancy, and originate in the high risk source area identified in Figure 1.
2) 20 droplets are released every 5 days, at each model grid cell of the source area, within the top vertical layer. They are then followed over the 15 days following their release. A total of 5,624,000 particles were released over the 10 years simulation period.

3) The droplets move vertically and horizontally due to advection by the ocean currents and by turbulent diffusion (modeled as random walk behaviour).

4) The simulated droplet drift tracks are processed and seasonal statistical parameters of their distribution are produced, such as 2D histograms of positions, covariance ellipses, and vertical distributions.

In the simulations described above, the movement of the simulated droplets is controlled uniquely by the oceanic circulation, mostly within the upper mixed layer. Although this simple approach is a useful tool to better understand the control of the ocean currents on the drifting oil, it does not include other forcing factors which, at times, can be significant, such as the direct effect of the wind and the waves on the oil patch.

5. Results

5.1 Seasonal droplet dispersion: an example

Figures 4-6 present the horizontal positions of particles, 15 days after their release from a single grid point within the source area, for each season (J-M, winter; A-J, spring; J-S, summer; O-D, fall). The point source for this example is located near the center of the source region, off the southwest shore of Banks Island. For each of the seasons, a total of about 3600 particles are included (20 particles every 5 days, for 3 months, over 10 years). In addition, a covariance ellipse characterizes each of the daily distributions. The centre of the blue ellipse indicates the mean position of the particles at the end of each of the 15 days of integration and it is oriented along the main axis of the distribution (the direction in which the particle scatter is the largest). The length of its axis is determined by the variance of the data along and perpendicular to the main axis.

In autumn, most particles drift up the coast, in a northward direction, forced by the predominantly downwelling (northward) wind (Figure 4). However, because of the variability in the wind direction, some of the droplets drift south and across Hecate Strait. After 15 days, the oil particles have moved an average distance of about 50 km, with the major half-axis of the covariance ellipse of similar length.

In winter, the situation is similar to the fall case: most of droplets drift north along the coast (Figure 5). However, at this time of year, the coastal winds blow more consistently to the north, and fewer particles go south. In addition, northward downwelling winds will tend to drive surface waters towards the coastline, and limit the offshore drift of the particles. Consequently, the particle distribution is more unidirectional, with flatter covariance ellipses, and most of the particles remain close to the coast.

In the spring, the strong southeasterly winds, dominant in winter, are not as frequent, and the distribution of the particles change accordingly: more particles drift away from the coast, across Hecate Strait (Figure 6). The covariance ellipses of the distribution are not as flat as the winter ones, although most of particles still drift northward.

The summer particle distribution is significantly different: an important fraction of the oil drifts offshore to the south-west and across Hecate Strait. Also, in contrast to the rest of the year when most particles drift up the coast (northward), the summer distribution is spread more evenly, with particles drifting along the coast south and north of the source. The covariance ellipses are more circular and the centers remain closer to the source. The change in particle distribution is related to the seasonal change in coastal winds: in summer, the local wind is not as strong and the prevailing direction is from the northwest (upwelling wind).

In addition to being advected horizontally, the neutrally buoyant oil particles are also displaced vertically under the action of the vertical ocean currents and turbulence. The resulting vertical distribution of the particles released from the one test location (star on Figure 1) is given in Figure 8. The vertical position of the centre of mass for all particles, as well as the spread (root mean square (rms) distance from the centre of the particle distributions), are given as a function of time. In all cases, within a few hours of integration, the particles that are initially seeded at the surface quickly spread vertically within the surface mixed layer. The thickness of this surface mixed layer varies seasonally, from a minimum in summer to a maximum in winter. In the vicinity of the source point, this surface layer is about 10 m deep in summer and 35 m deep in winter. This is reflected in the initial (day 1) vertical distribution of the particles which are confined to the top 10 (35) m in summer (winter). Spring and fall are transitional periods, with initial distribution spread over intermediate depths of 15 m and 25 m, respectively. Following this initial vertical spread, the vertical distribution slightly deepens with time because of 1) some of the particles move into deeper water where the model vertical layers thicken, and to a lesser extent 2) vertical diffusion.

5.2 Temporal and spatial variability of the total droplet distribution

In this section, we describe the distribution of the complete ensemble of particles (a total of 5,624,000 particles) released in the 10 year simulation, over the source area. The first question addressed is the likelihood of a particle being within the source area during the 15 day following its release. The probability that a particle will be located within the source area over the 15 day period following its release varies around 60 % (Figure 9 and Table 1), with minimum values in summer and maximum in fall and winter. In summer, more particles leave the source area, mostly drifting offshore during upwelling wind events. In some years (1999 and 2006), summer upwelling winds were more prevalent, and more than 50% of the oil particles were found outside of the source area (Figure 9).

The 10 year mean horizontal distribution of oil droplets over the 15 day integration period is shown in Figures 10 and 11. The distribution gives the particle concentration, as a fraction (%) of the total number of released particles . The overall mean distribution of the droplets indicate that most particles remain within 50-km of the source area (Fig 10). Most of the oil remains close to the mainland, drifting northward for the most part. A few particles leave the coast to cross Hecate Strait and reach Haida Gwaii. The seasonal variability of the horizontal oil distribution is given in Figure 11. In winter, most of the particles drift along the coast, with few oil droplets crossing Hecate Strait. On the other hand, in summer, the mean distribution extends further offshore, into Hecate Strait, and more of the oil droplets reach Haida Gwaii, mostly on the south west coast of Moresby Island. Fall and spring are transition periods, with the fall (spring) distribution approaching winter (summer) conditions.

5.3 Potential impact of oil spill on remote coastal areas

Given that most of the oil remains within the source area, the highest impact of an oil spill will be near the source region. Nevertheless, some of the spilled oil could reach relatively remote coastal areas. To estimate the potential impact of oil spill in regions away from the source area, we divided the northern BC coastline into several regions of interest (Figure 12): North Shore (immediately north of the source area), Central Shore (south of the source area), Southern Alaska, and 2 sections of the east coast of Haida Gwaii (northern Graham Island and southern Moresby Island). The impact of oil spilled within the source area was estimated, for each of these remote sections of the coast, by the relative number of droplets drifting into these areas.

The fraction of the oil droplets found along each of the remote coastal sections is presented in Figure 13 and Table 2. Over the 10 year integration, very few particles drift onto the northern section of Haida Gwaii (1 out of 100,000), and the results are too small to be included in Figure 11. In agreement with the results presented above, the highest impact is found closer to the source region, i.e. along sections of the BC coast located north and south of the source area. A much smaller number of oil droplets (less than 0.3%) reach the Southern Alaska and the Moresby Island coast and the Moresby Island region.

The potential impact of spilled oil for each of the coastal sections varies with the seasons (Figures 13-18). In fall and winter, more particles drift northward, with relatively greater impact in North Shore and Southern Alaska areas. On the other hand, the oil spill impact for the Moresby Island and Graham Island regions is potentially larger in spring and summer, when the offshore drift induced by the ocean circulation is more prevalent. In fact, for areas further away from the source, such as Southern Alaska or Moresby Island, the oil spill impact depends more strongly on seasons. In the case of the Southern Alaska coast, about 80% of the particles enter the area in winter and fall (Figure 16). This means that the probability of an oil particle reaching the Southern Alaska region in winter is 6-7 times higher than in summer. In contrast, the probability of a particle to reach Moresby Island is 18 times higher in summer than in winter (Figure 17).

6 Discussion and conclusion

Using a combination of 2 numerical models, ROMS BC Coast circulation model and LTRANS Lagrange particle tracking software, we estimated transport of oil droplets originating from the coastal waters in the vicinity of the entrance to Douglas Channel, on the northern British Columbia coast. Results from the ROMS circulation model were used as input to LTRANS which simulated the drift of oil droplets continuously seeded by oil droplets, over a 10 year period (1998-2007). Some statistics of the resulting droplet distribution are presented in order to

describe its spatial and temporal variability. The modeled droplet distribution is found to be strongly seasonal. In fall and winter, when downwelling (northward) wind dominates, the majority of the oil droplets drift northward along the coast of BC and Southern Alaska. In summer, more of the particles move offshore across Hecate Strait, onto the eastern coast of Moresby Island.

To keep the problem simple and tractable, the model results have been obtained under a series of simplifications. For example, the simulated oil spill droplets were attributed neutral buoyancy, and rapidly spread over the ocean mixed layer. A more realistic simulation would have to include the effect of the density of the oil product relative to the surrounding water. Also, in this study, the movement of the oil particles is solely due to advection by the ocean currents and turbulence, , and does not account for the potential effect of transport due to wave induced Stokes drift Stokes wind or direct forcing of the oil patch by the wind. A more elaborate modelling study, including the all of the above mentioned dynamics, would provide a more complete analysis.

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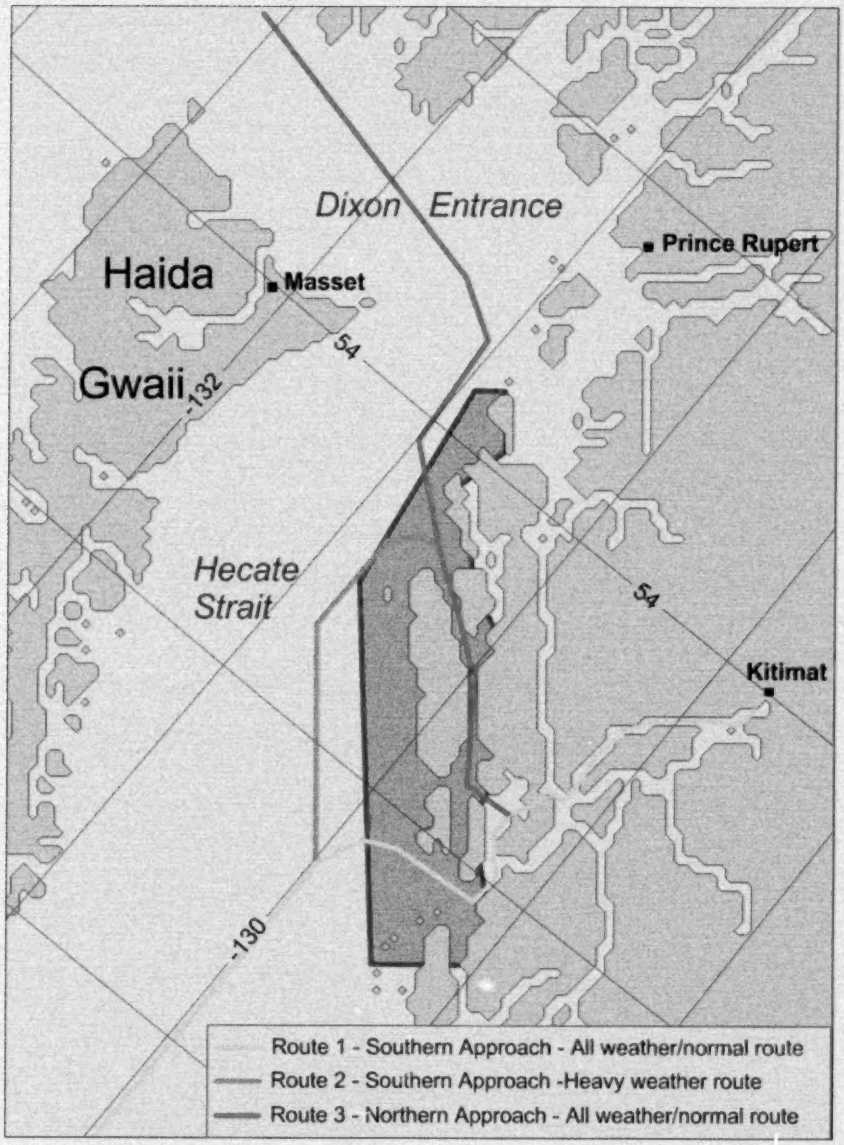
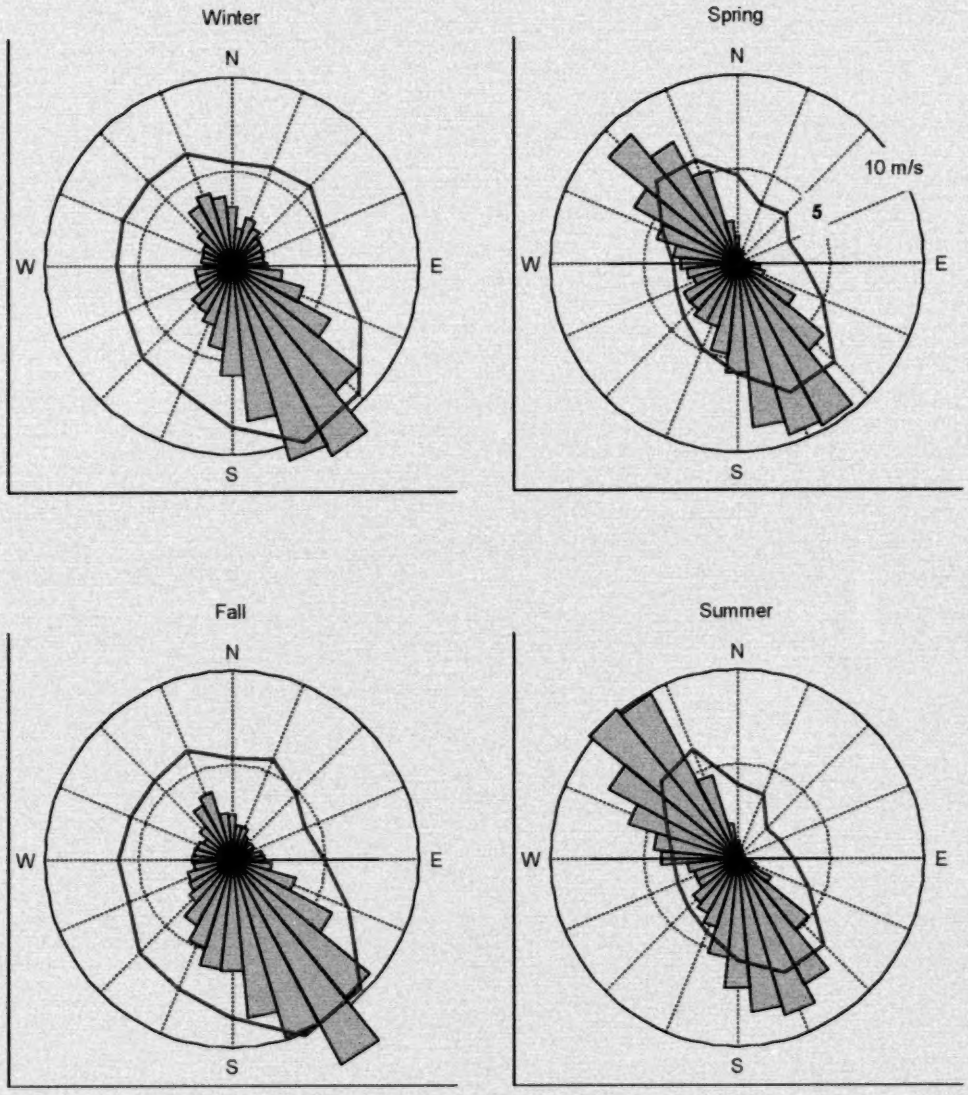


Figure 1. Enbridge proposed tanker routes, and source area of simulated oil spills (purple area).



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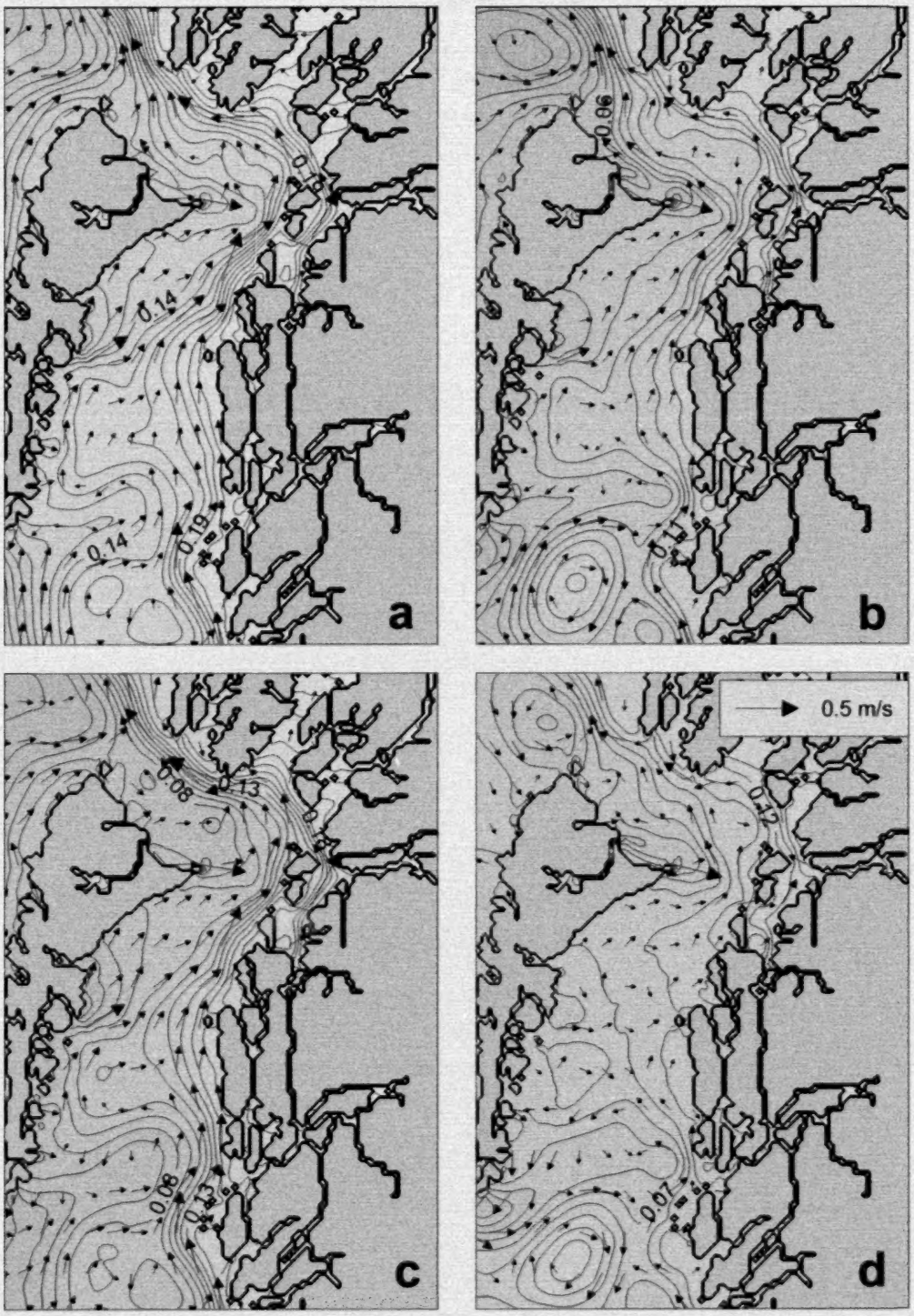

Figure 3. Mean seasonal surface currents over the 10 year simulation (a: winter, b: spring, c: fall, d: summer). The contours indicate the mean sea level (m).

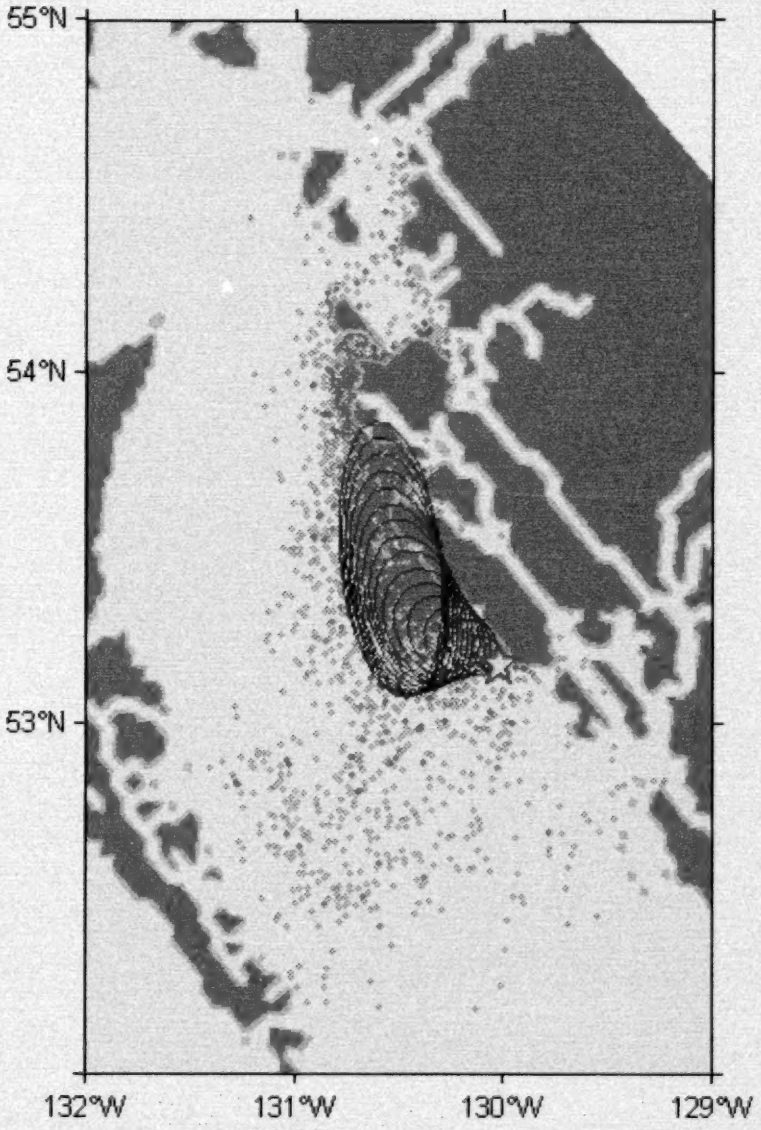

Figure 4. Distribution of oil droplets, 15 days after their release from one single point source (indicated by the star), during the fall season. In blue are the daily covariance ellipses (see main text for details).

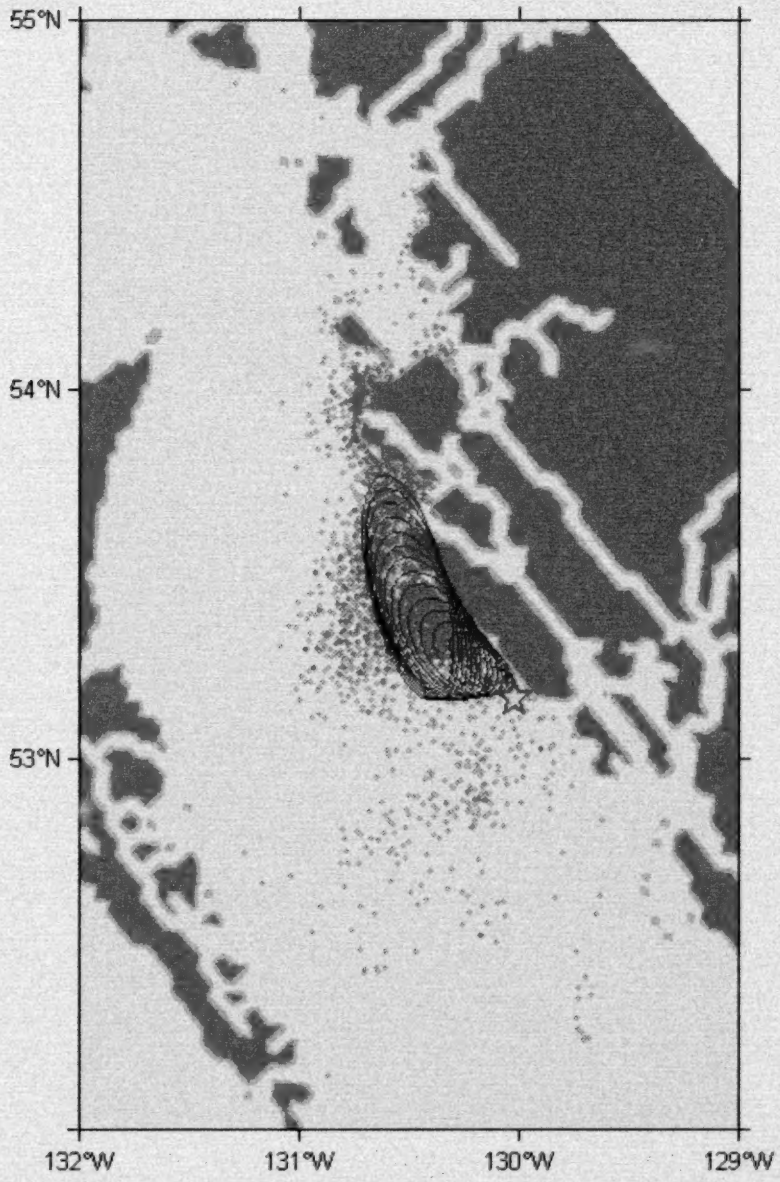

Figure 5. As in Figure 4, but for winter.

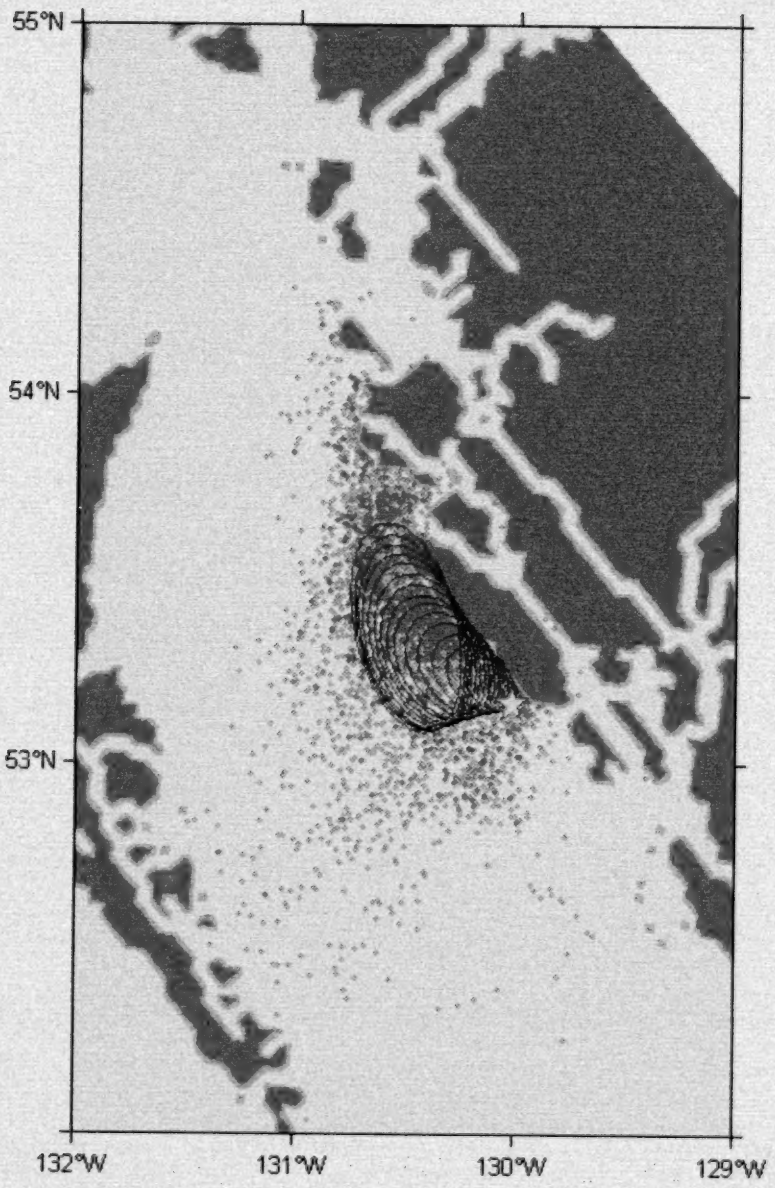

Figure 6. As in Figure 4, but for spring.

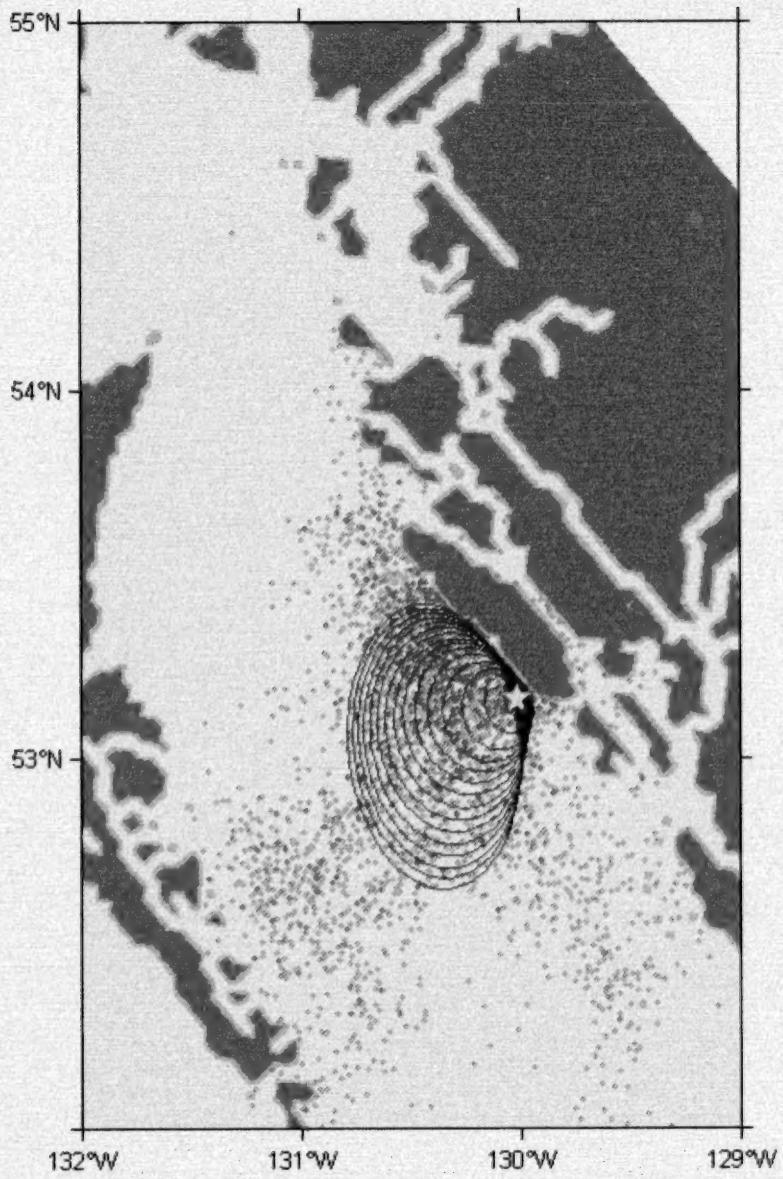

Figure 7. As in Figure 4, but for summer.

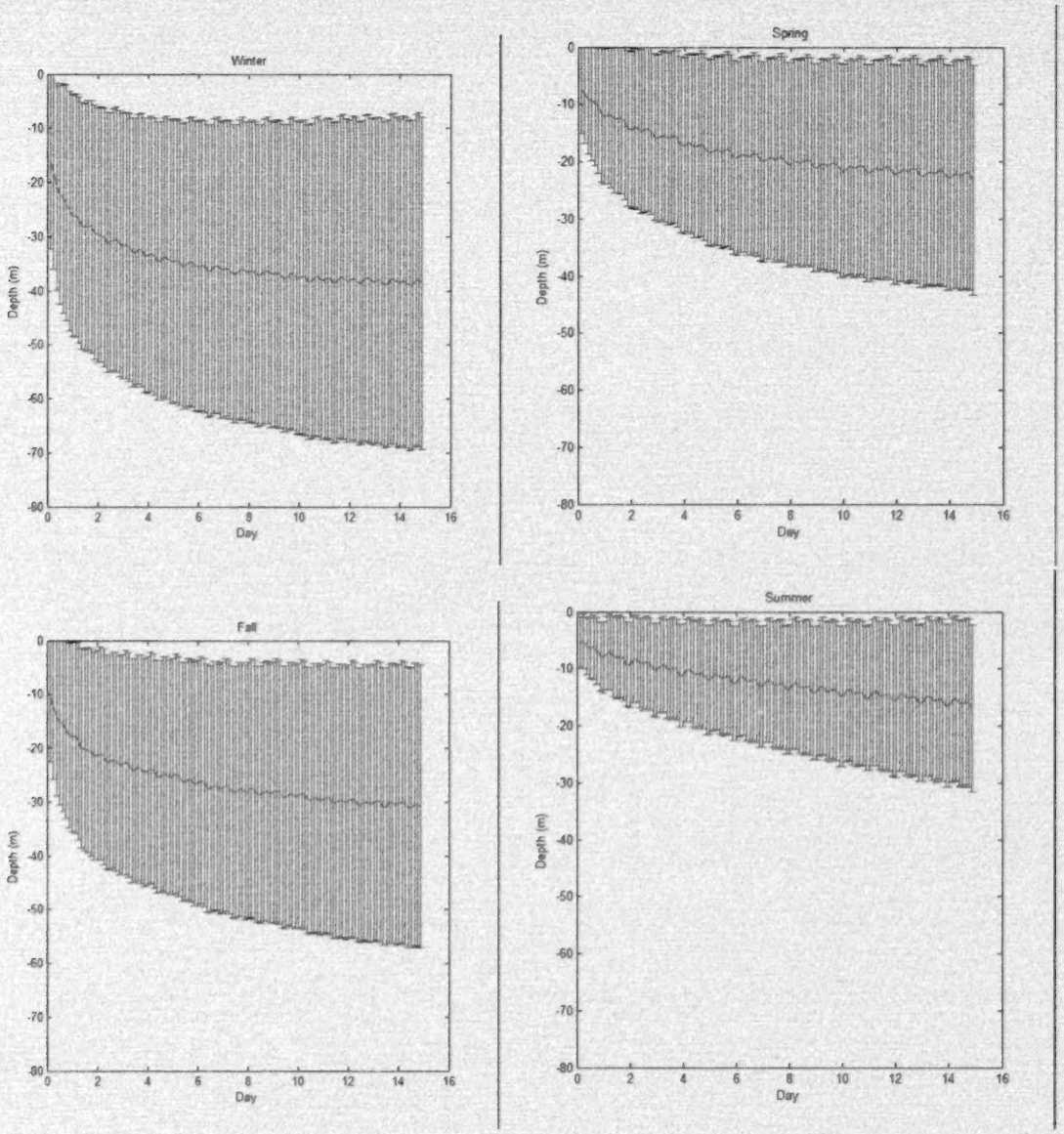

Figure 8. Seasonal vertical distribution of the oil droplets released from the test location (star on Figure 1).

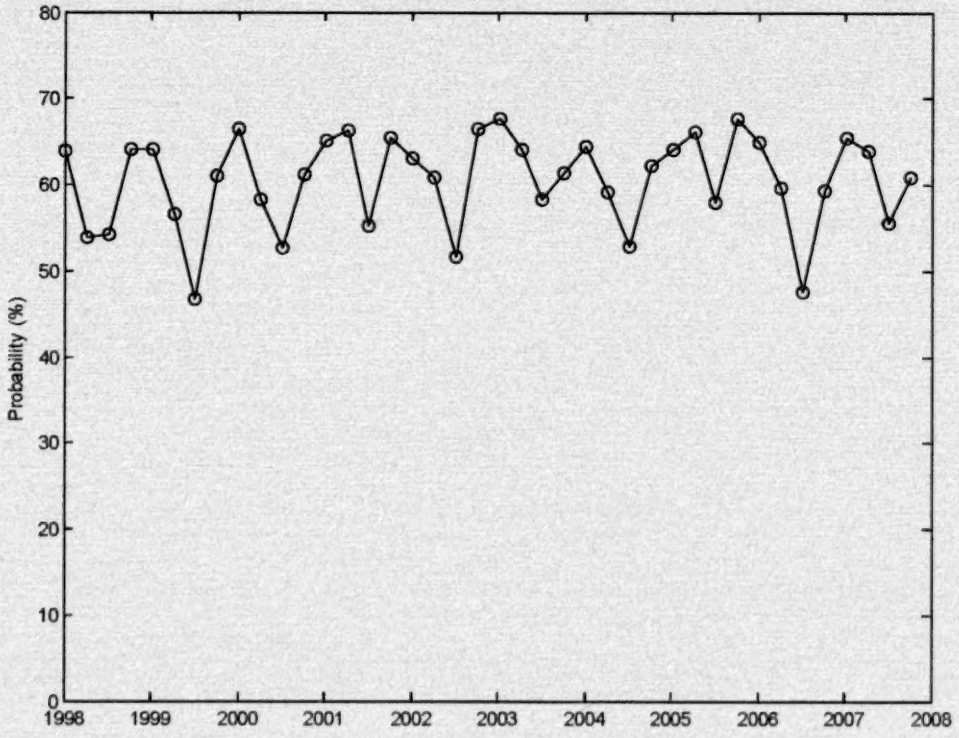

Figure 9. Probability (%) for a droplet to be found within the source area, during the 15 day period following its release.

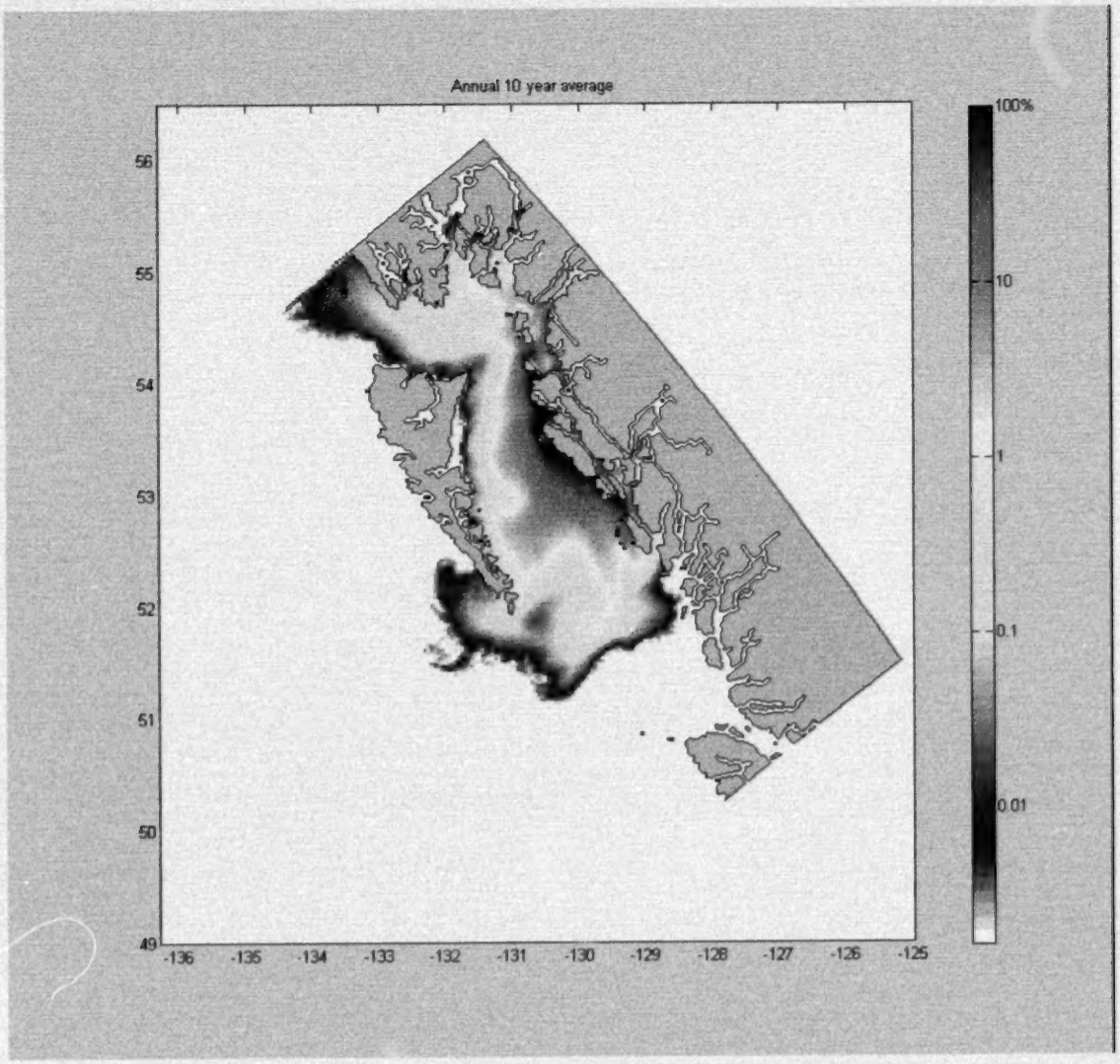

Figure 10. 10-year average horizontal particle distribution, over the 15 day integration period.

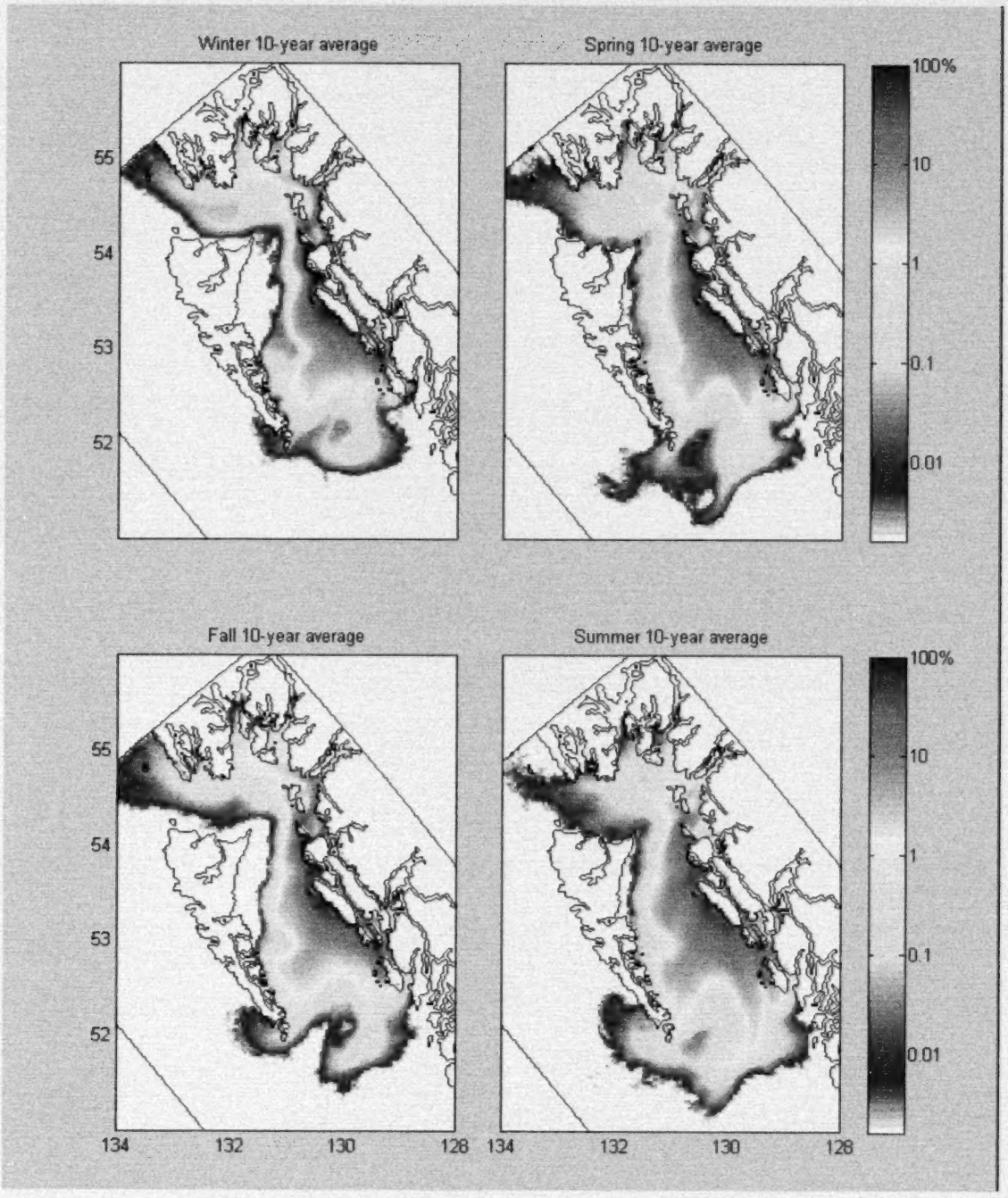

Figure 11. As in Figure 10, but for each season.

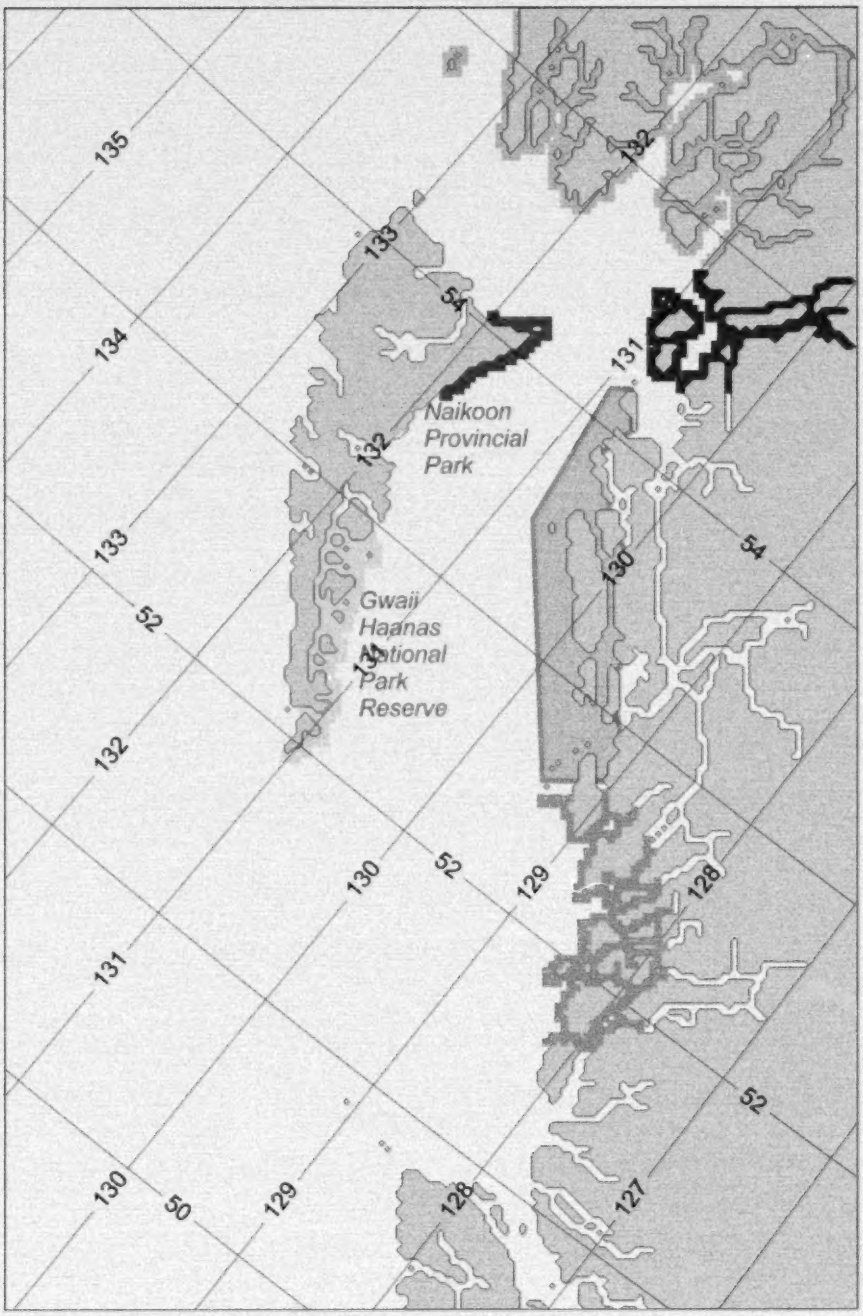

Figure 12. Source area (pink), as well as 5 remote coastal areas (orange: Central BC, blue: northern BC, olive: Alaska, violet: Graham Island, Green: Moresby Island).

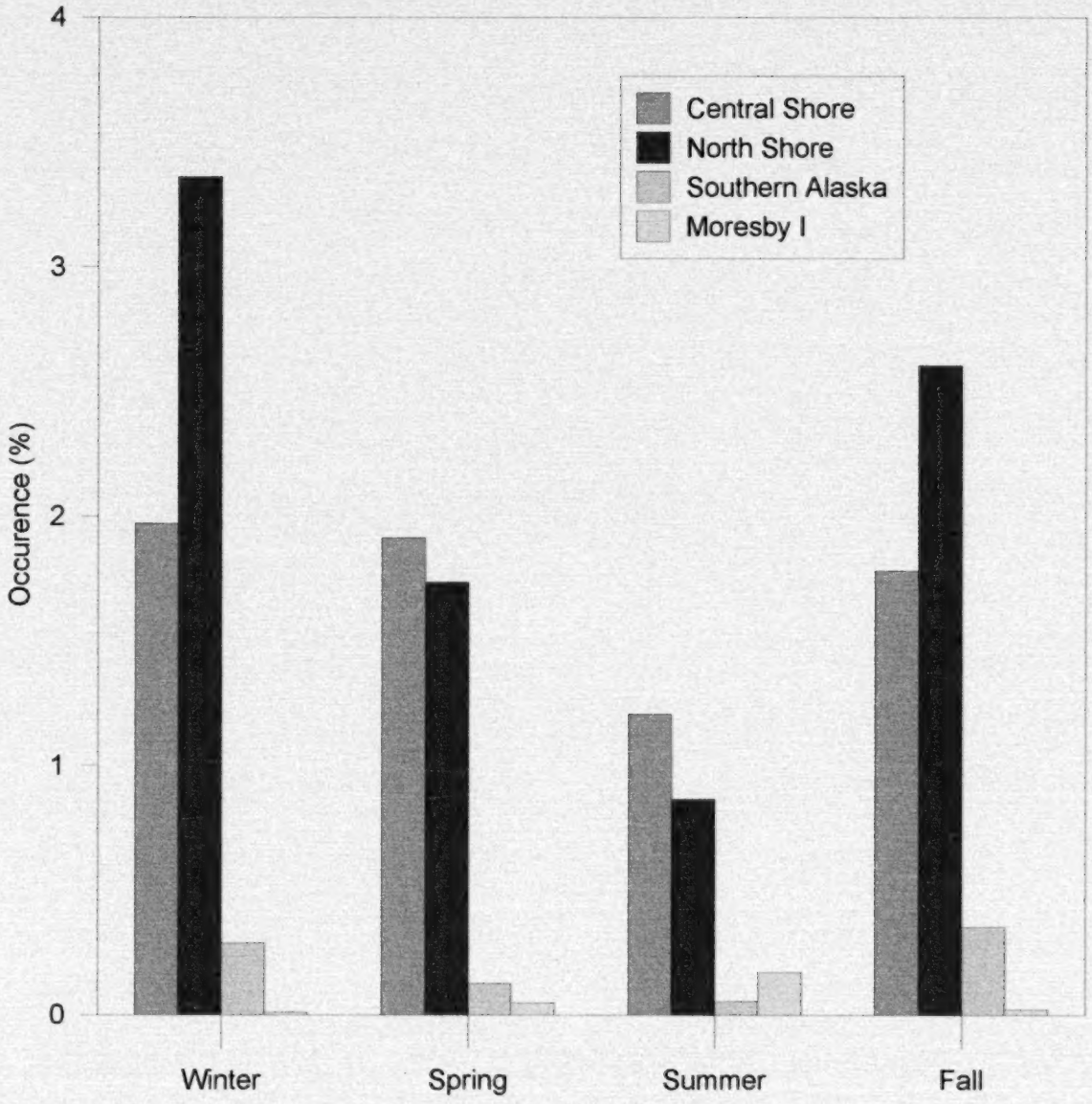

Figure 13. Occurrence (%) of the droplets in the coastal zones identified in Figure 12.

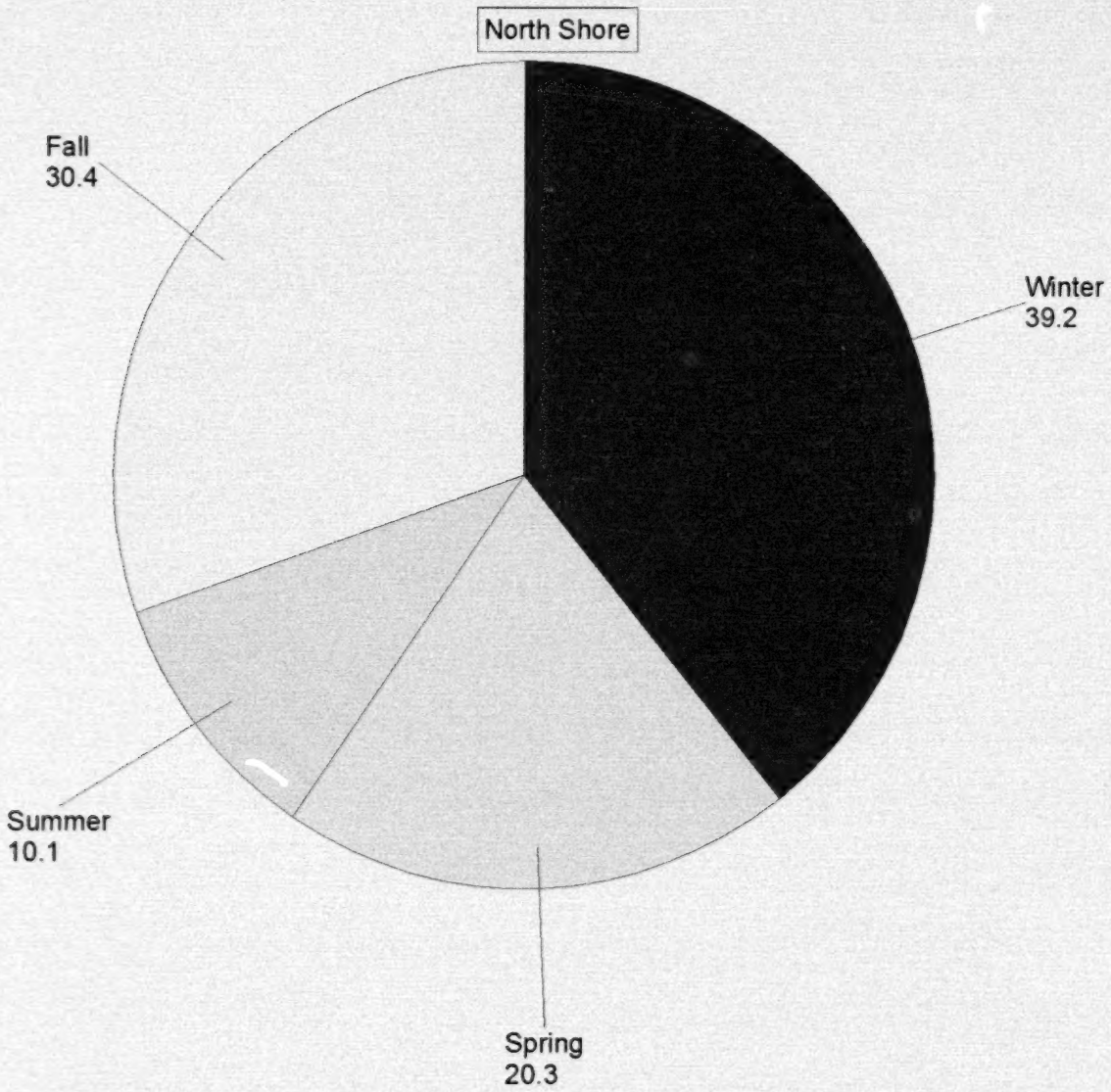

Figure 14. Seasonal relative occurrence (%) of the droplets within the North Shore Region.

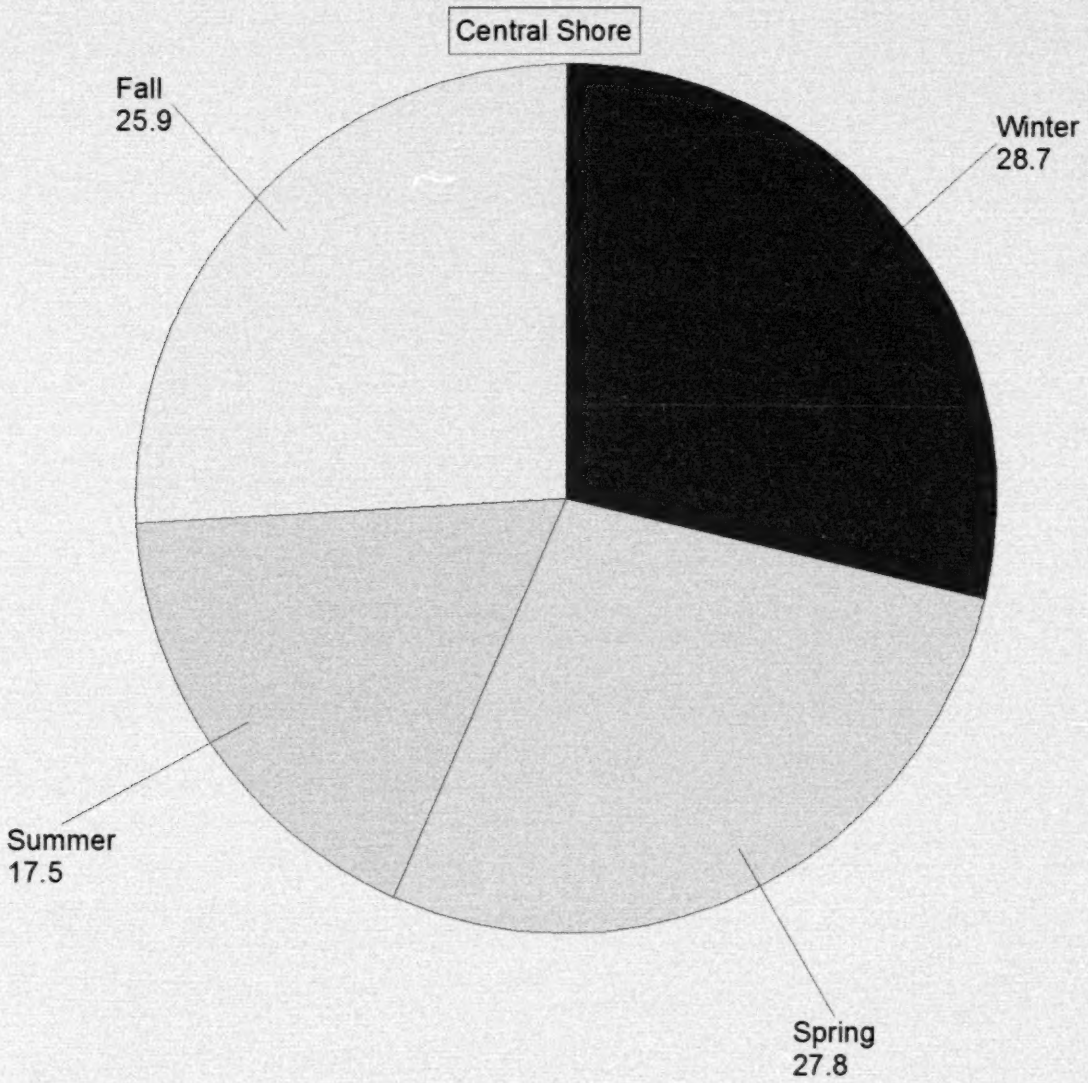

Figure 15. As in Figure 14, for the Central Shore area.

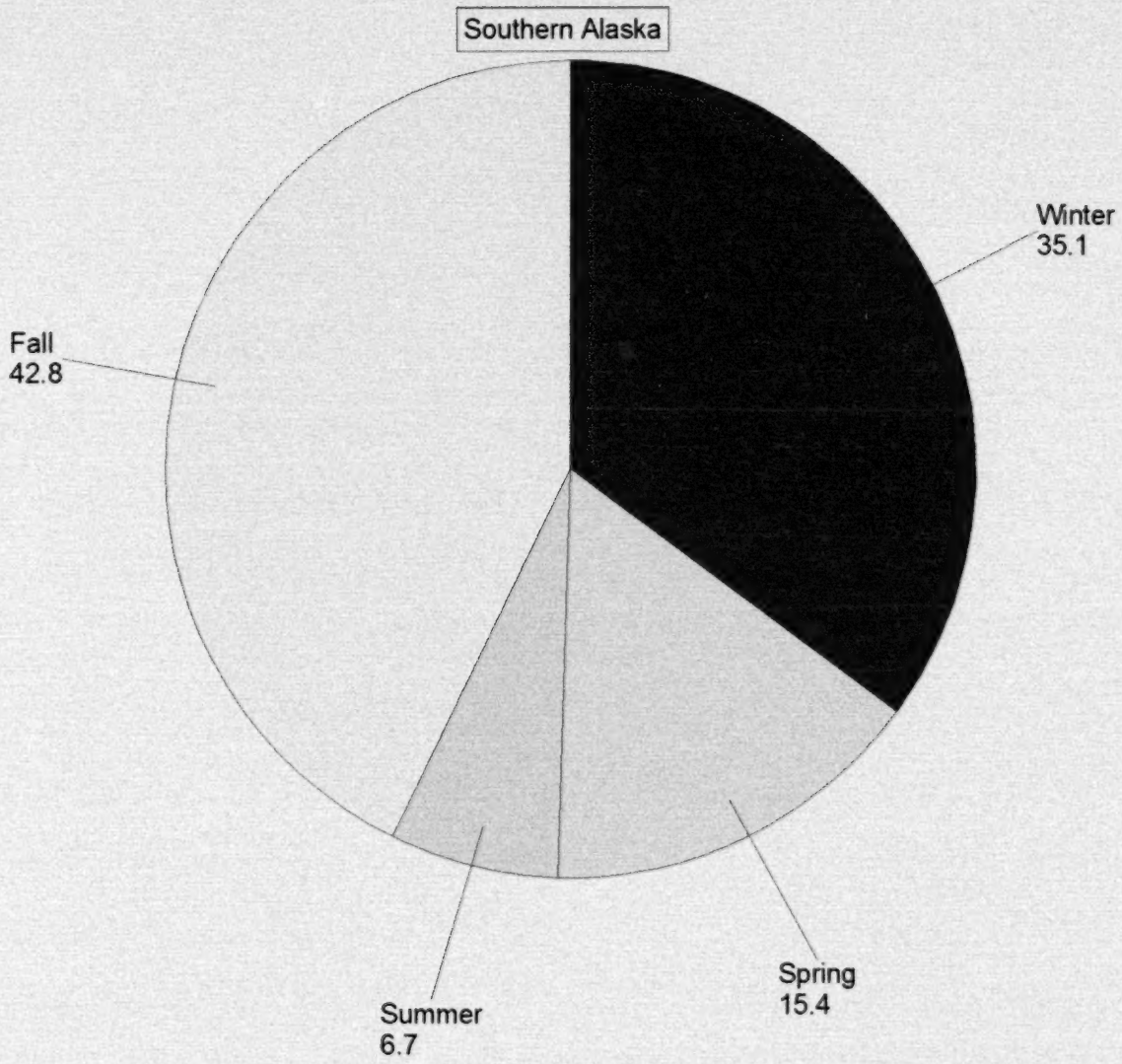

Figure 16. As in Figure 14, for the Southern Alaska area.

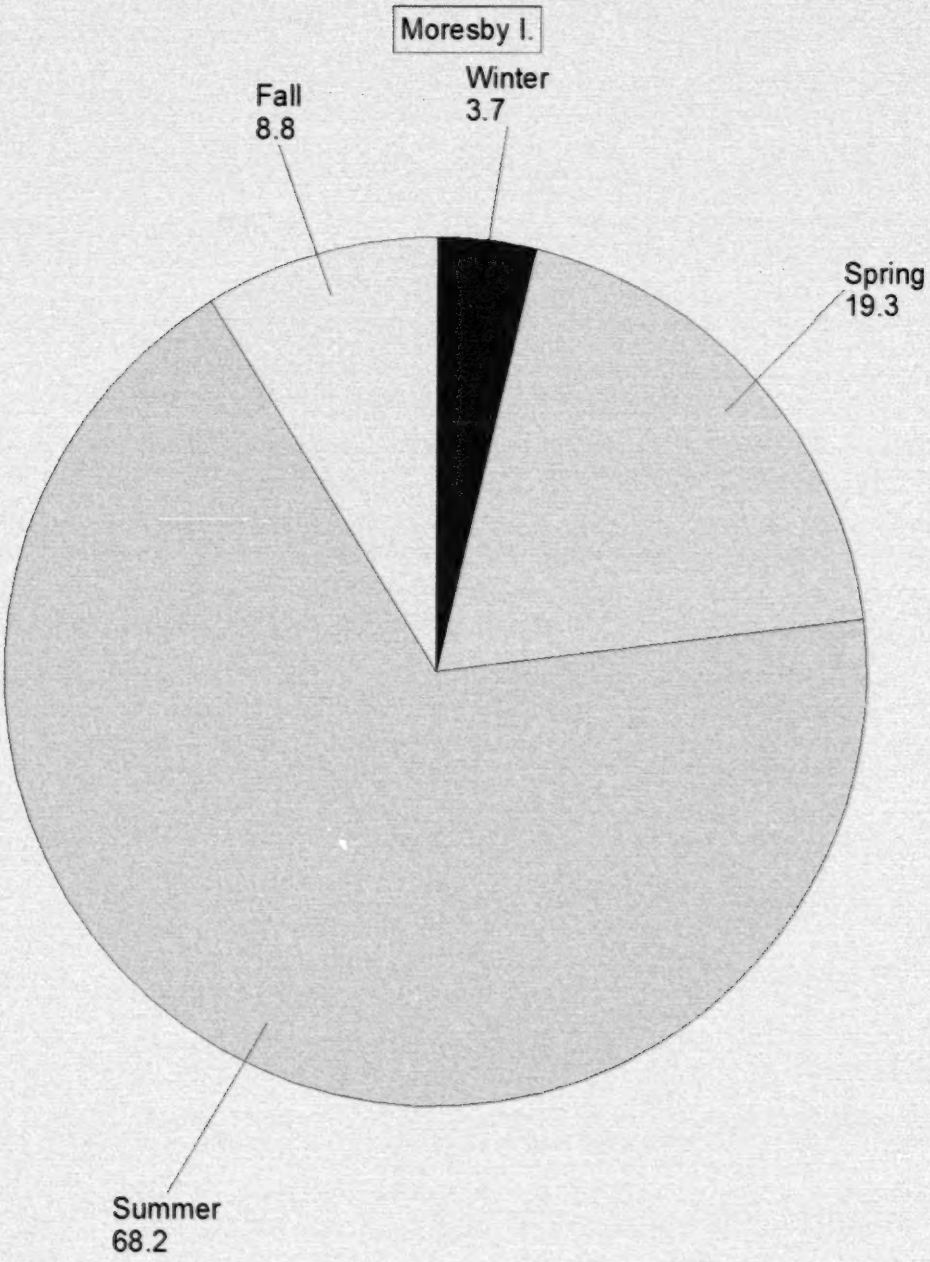

Figure 17. As in Figure 14, for the Moresby Island area.

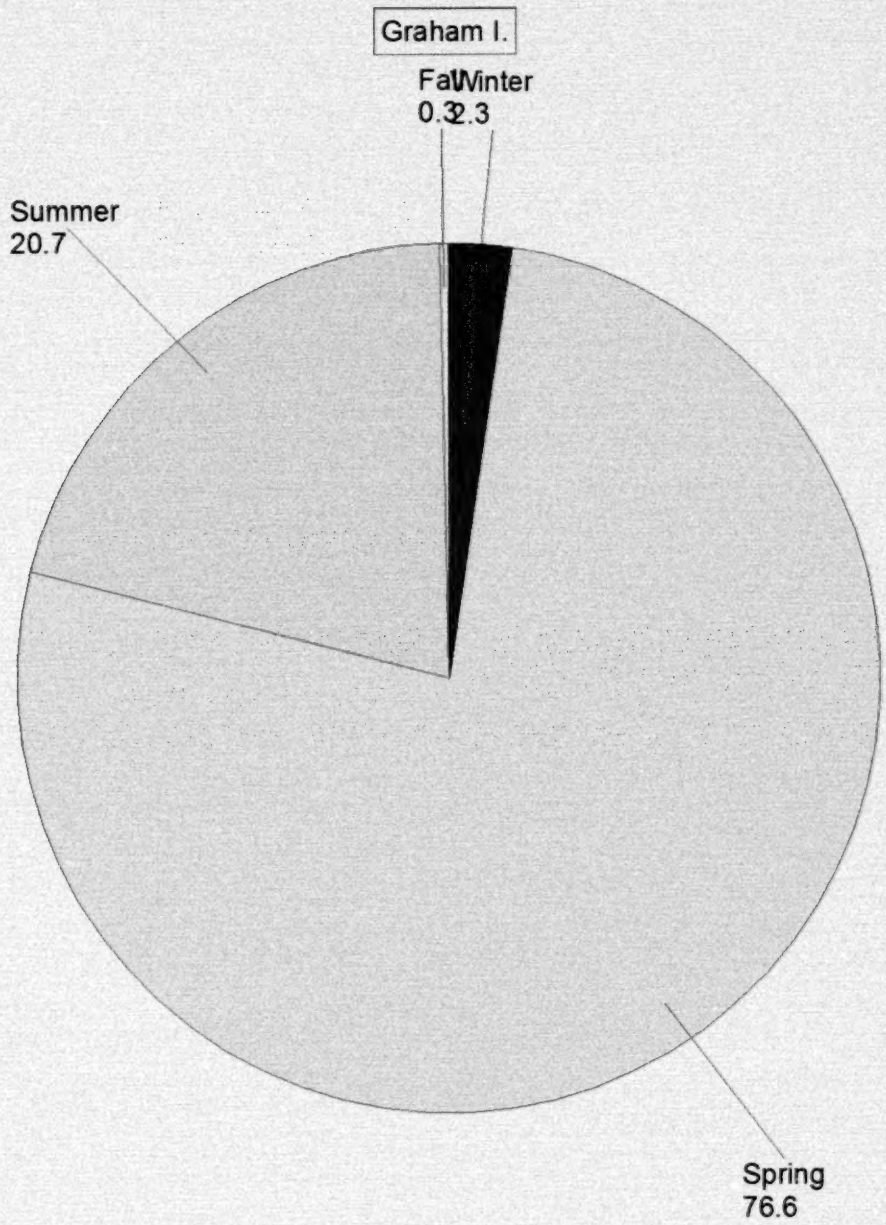

Figure 18. As in Figure 14, for the Graham Island area.

Table 1. The fraction (%) of oil droplets found within the source area, in the 15 day integration period.

Winter	Spring	Summer	Fall	Annual mean
64.9	60.9	53.2	62.9	60.5

Table 2. The fraction (%) of oil droplets found within each of the remote coastal areas.

	Winter	Spring	Summer	Fall	Annual mean
BC North Shore	3.36	1.73	0.86	2.60	2.14
BC Central Shore	1.97	1.91	1.21	1.78	1.72
Southern Alaska	0.29	0.13	0.055	0.35	0.21
Moresby Island	0.009	0.049	0.171	0.022	0.063
Graham Island	0.0000	0.0028	0.0008	0.0000	0.0009